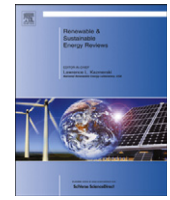
Renewable and Sustainable Energy Reviews 16 (2012) 5584–5596

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



The effect of temperature on various parameters in coal, biomass and CO-gasification: A review

Leila Emami Taba, Muhammad Faisal Irfan [*,1], Wan Ashri Mohd Wan Daud, Mohammed Harun Chakrabarti

Department of Chemical Engineering, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia

ARTICLE INFO

Article history:
Received 19 May 2011
Received in revised form
5 June 2012
Accepted 8 June 2012
Available online 4 August 2012

Keywords:
Coal, biomass
CO-gasification
Temperature
Gas yield
Carbon conversion

ABSTRACT

Numerous reviews have been found related to individual studies on coal gasification (CG) and biomass gasification (BG). However, this review deals mainly with the CO-gasification (COG) of numerous types of coal and biomass and then compares their results with those obtained using coal and biomass gasification in detail. There are several process parameters which have a direct effect on the gasification process and among them temperature is the most significant one. In this paper, the production of H_2, CO_2, CO, CH_4, and other hydrocarbons in CG, BG and COG with the variation of temperature is reviewed in detail. As it mainly influences the gaseous products and their characteristic behaviour, this review takes into account the effect of temperature on various other parameters such as carbon conversion, gas yield, calorific value, cold gas efficiency as well as tar and char contents in various kinds of coals, biomasses and their mixtures under catalytic or non-catalytic conditions.

Contents

Abbreviations: AS, almond shells; BG, biomass gasification; CG, coal gasification; CH, chestnut tree residue; COG, CO-gasification; CCG, catalytic coal gasification; CBG, catalytic biomass gasification; CCOG, catalytic CO-gasification; DT, high volatile bituminous coal from China; EB, eucalyptus; EFB, empty fruit brunches; ER, equivalent ratio; FR, feed rate; HV, Semi anthracite coal from Spain; HHV, high heating value (MJ/m3); LHV, low heating value (MJ/m3); NCCG, non-catalytic coal gasification; NCBG, non-catalytic biomass gasification; NCCOG, non-catalytic CO-gasification; NCV, net calorific value (MJ/m3); OS, olive stone; PAH, polycyclic aromatic hydrocarbons; PC, pet coke; PE, poly ethylene; PET, poly ethylene terephthalate; PT, high volatile bituminous coal from Spain; RDF, refused derived fuel; SA, medium volatile bituminous coal from South Africa; VOC, volatile organic compounds

* Corresponding author. Tel.: +603 7967 5206; fax: +603 7967 5319.
E-mail address: muhammadfipk@gmail.com (M.F. Irfan).
[1] Present address: Department of Chemical and Materials Engineering, University of Alberta, T6G 2V4, Edmonton, Alberta, Canada.

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2012.06.015

Nomenclature

H	height (m)
ID	internal diameter (m)
P	pressure (N/m^2)
PP	partial pressure (N/m^2)
T	temperature (°C)

1. Introduction

The increase in the global energy consumption in recent years has led to an alarming rise in emissions of CO_2, NO_x and SO_x into the environment. This increase of CO_2 emission from fossil fuels has a dominant influence on the atmospheric CO_2 concentration that eventually results in rising global temperatures and sea level. According to the International Energy Outlook [1], world energy-related CO_2 emission will increase from 30.2 billion metric tons in 2008 to 43.2 billion metric tons in 2035. In terms of per capita emission, CO_2 emission is approximately at a value of 4.29 Mt for the entire world [2]. According to the Kyoto Protocol, developed countries should reduce their total emissions of greenhouse gases between the years 2008 and 2012 by at least 5% from the level reported in 1990.

Coal has the largest reservoir in the world compared to the other energy sources like oil and gas according to the BP statistics review of the world's energy [3]. Due to the common availability of coal and its cost feasibility, most of the developed countries use coal as a fossil fuel for power generation. However if some countries have a deficit in coal resources then they mainly import from the coal enriched countries.

Biomass is a major renewable energy source and one of the environmental friendly fuels that contains less sulfur and ash contents and also has higher volatile matter than coal due to which it is likely to be an attractive clean fuel for reducing greenhouse gas emissions. Biomass is described as plant material such as wood, agricultural crops and their residue as well as industrial and municipal wastes due to their high percentage of food waste and fibre. Biomass can be used in different processes such as combustion, pyrolysis and gasification to provide gaseous fuels. From a global perspective, after coal, petroleum and natural gas, biomass is the most important source of energy which can supply about 14% of the world's energy consumption [4]. Gasification is a clean technology that converts different carbonaceous feed stocks such as natural gas, coal, petroleum, coke, biomass and municipal solid wastes in a limited supply of air to gaseous products such as hydrogen and carbon monoxide (syngas), carbon dioxide, water as well as gaseous hydrocarbons at high temperatures. It also produces solids such as char, ash and condensable products like tars and oils. Gaseous products can be used to produce electricity, hydrogen, chemicals and liquid transportation fuels. Gasification in oxy-fuel combustion produces high amounts of CO_2 which can be easily captured and sequestrated, so it is more effective than direct combustion of coal in air for capturing and sequestering CO_2. It can be integrated with other technologies such as combustion turbines and solid oxide fuels for advanced power generation [5,6]. Coal gasification (CG) is the process of producing a fuel-rich product, which is a highly concentrated stream of hydrogen and syngas ($CO+H_2$). Although, CG has some advantages because of the availability and low cost of coal it still has the drawback related to the consumption of fossil fuels which have caused a serious global energy crisis with significant environmental impact. Biomass gasification (BG) is also a promising and advanced technology for extracting the energy of biomass and has received increasing attention in the energy market, in which hydrogen is produced from high-temperature gasification and low-temperature pyrolysis of biomass. BG has some advantages such as the reduction of fossil fuel dependency in addition to lowering emissions of CO_2, NO_x and SO_x because of the high volatile matter content of biomassthat results in the production of significant quantities of bio-oil. However, BG has some disadvantages due to season availability as well as the low heating value of biomass.

In recent years, some researchers have reported that the combination of both coal and biomass is more advantageous than their individual effects as shown in Table 1. It allows one to use biomass on a commercial scale and coal in an environmentally friendly way. CO-gasification (COG) of coals having high ash and sulphur content along with different kinds of renewable resources such as biomass and wastes is a promising technology; biomass and wastes cause the reduction of harmful gases such as CO_2, NO_x and SO_x. Higher reactivity of biomass improves the gasification process [5,7]. The most effective catalysts in carbon gasification are alkali metal salts, especially potassium. However, they are expensive and most of the potassium salts are converted into gaseous phase at high temperatures during CG. Also in COG, biomass, especially the herbaceous type has high alkali content (particularly potassium) which plays a role of an inexpensive catalyst source [8,9]. Since BG produces large amounts of tar, so when biomass and coal are gasified together, the produced tar is converted to a gaseous form because of the high temperatures of operation [10]. The heterogeneity of biomass and wastes causes an increase of fluctuations in quality, availability and composition and hence their processes are more complicated than that of coal, so in COG, coal plays the role of a buffer and a bed material to improve the quality of biomass particles. Biomass has low calorific value and density which causes an increase in the cost of transportation and storage, hence COG of biomass with coal is more economical than that of biomass alone [7,11]. COG of coal and biomass produces both desirable and undesirable components such as syngas and heavy hydrocarbons, tars, solid and gaseous pollutants, respectively, that can be reduced by cleaning the gas or using catalysts (dolomite, fluid catalytic cracking catalysts, metal catalysts, Y-zeolites, alkaline catalysts, and steam reforming catalysts [12] for promoting tars and other hydrocarbons in further reactions.

There are several process parameters which may affect the gasification process and among them temperature is the most important one. In this paper, the effect of temperature on the production of gaseous derivatives and other hydrocarbons and their gaseous ratios in catalytic and non-catalytic CG, BG and COG is reviewed. Moreover, in this review, the influence of temperature on carbon conversion, gas yield, calorific value, cold gas efficiency, tar and char contents on various kinds of gasification processes is described.

2. Gasification mechanism

The main reactions involved during the gasification of coal, biomass or their blends are summarized below [12,13]:

Boudouard:

$$C+CO_2 \rightarrow 2CO \quad \Delta H=172.5 \text{ kJ/mol} \tag{1}$$

Water gas:

Primary:

$$C+H_2O \rightarrow CO+H_2 \quad \Delta H=131.3 \ kJ/mol \tag{2}$$

Secondary:

$$C+2H_2O \leftrightarrow CO_2+2H_2 \quad \Delta H=90.2 \ kJ/mol \tag{3}$$

Methanation:

Table 1
Comparison between coal, biomass and CO-gasification processes.

Properties	Coal gasification	Biomass gasification	CO-gasification
	Fossil fuels	Renewable resource	Reduction of the fossil fuels dependency & using neutral and renewable resource
Ash	High	Low	Low
Sulfur	High	Low	Low
Nitrogen	High	Low	Low
Reactivity	Low	High	High
Volatile matter	Low	High	High
Alkali compounds (calcium and potassium)	Low	High	High
Porosity of remaining char	Low	High	High
Energy density	High	Low	High
Bulk-density	High	Low	High
Calorific value	High	Low	High
Moisture content	Low	High	Low
Availability	No season limitation	Season limitation and heterogeneity	No season limitation and stable gasification condition
Abrasion	No abrasion	Anomalistic shape, abrasion	Coal or coke particle serve as bed for biomass abrasion reduced & power saved
Transportation & storage costs	Low	High	Low
Environmental pollution	Increase	Decrease	Decrease in NO_x,SO_x,volatile organic compounds (VOC)
Scale	Large		Large (economically)
Gasification temperature	High	Low	High
Carbon conversion	Low	High	High
Gas yield	Low	High	High
Tar production	No	Yes	Low
Char production	Yes	No	Low
Efficiency	Low	High	High

$$C+2H_2\leftrightarrow CH_4 \quad \Delta H=-74.9 \ kJ/mol \tag{4}$$

Water gas shift:

$$CO+H_2O\leftrightarrow CO_2+H_2 \quad \Delta H=-41.2 \ kJ/mol \tag{5}$$

Steam reforming:

$$CH_4+H_2O\leftrightarrow CO+3H_2 \quad \Delta H=206.2 \ kJ/mol \tag{6}$$

Dry reforming:

$$CH_4+CO_2\leftrightarrow 2CO+2H_2 \quad \Delta H=247.4 \ kJ/mol \tag{7}$$

3. Effect of temperature

Temperature is one of the most significant operating parameters, which has an effect on the gaseous composition and carbon conversion throughout the oxidation and gasification reactions. Gas yield, heating value, cold gas efficiency and finally char and tar yields in gasification processes are affected by temperature. This effect depends on thermodynamic behaviour of the reactions and the balance between endothermic and exothermic reactions [5,14–16].

There is a limitation to how high the temperature for the gasification process can go up to (tolerable level) due to its effect upon (1) the volatile matter content in fuels; (2) materials of construction used in the gasifier; (3) the production of undesirable gases such as NO_x; and (4) its effect on the ash fusion [11,14,15,17–19]. For example, for fluidized bed gasifiers, temperature limitation for CG is reported to be in between 750 and 1000 °C [15,17,20,21]. Similarly, the value of temperature limitation for BG is reported to be in between 550 and 900 °C. However this value is usually less than 900 °C due to the presence of high volatile matter content in biomass [19,22–25]. Moreover, this value for COG ranges between750 and 900 °C [11,14,26]. However, this value varies with different kinds of fuels as well as types of gasifiers used. The various types COG studies reported in the literature are summarized in Table 2.

3.1. Gaseous composition

3.1.1. H_2 concentration (%)

For various kinds of coals such as Shenwha (sub-bituminous coal), Australian (semi-anthracite to sub-bituminous), Fugu (sub-bituminous coal) and PT (bituminous coal) elevated bed temperature favours endothermic gasification reactions. The main endothermic reactions are primary and secondary water gas reactions, secondary cracking and reforming of heavy hydrocarbons/tars and several others. Due to the increase of these endothermic reactions the formation of H_2 also increases [13,15,17,27–31]. However, hydrogen production is higher under catalytic coal gasification (CCG) environments using various types of catalysts [Ni $(NO_3)_2$, K_2SO_4, Ni (NO_3)+K_2SO_4, K_2CO_3] than under non-catalytic ones due to an increase in the rate of the reaction [20,32]. Fermoso et al. [33] used different ranks of coals such as DT (high volatile bituminous coal from China) and SA (medium volatile bituminous coal from South Africa) and observed that coals having higher carbon contents and reactivity could react more with steam and produce higher contents of H_2. It was also reported that lignite volatiles contain more H_2 than bituminous volatiles [34]. CG in fluidized bed reactor at different temperatures and fluidization gas velocities produces higher amounts of H_2 at higher velocities due to the better mixing of solids, which results in an increase in the rate of reaction of coal [18].

BG is the most efficient and economical route for H_2 production and the primary emphasis in BG is to maximize the contents of H_2. BG is affected by different operation parameters such as composition and moisture contents of feed stocks, types of gasifier, residence time, pressure, gasifying agent, and most importantly temperature [35,36]. By changing temperature, a similar trend is observed as that of CG during the gasification of various kinds of biomass. With the rise of temperature, the production of H_2 increases during gasification of different biomass types such as EFB, sawdust holm-oak, pine wastes, eucalyptus, grapevine pruning wastes, wood pine, pine sawdust, legume straw, wood, grape and olive bagasse due to the increase in endothermic gasification reactions [37–52]. Moreover, Lahijani and Zainal [50] claim that the hydrogen production in gasification of sawdust is higher than that from EFB gasification due to the higher moisture content of sawdust than EFB. It is also reported that BG with biomass having high moisture contents (90–95%) play a main role in H_2 production because of supercritical water gasification [35]. Results also show that H_2 contents in

Table 2
Summary of previous CO-gasification studies.

Sample	Gasifier, specification	Particle size (μm)	Operating condition	Medium	Optimum obtained results	Ref.
Australian & Chinese bituminous coal, Cedar bark	Pressurized drop tube furnace	Coal A: 29 Coal F: 38 Cedar bark: 85	*T*: 1200–1400 °C *P*: 0.5 MPa *PP* CO_2: 0.05 MPa	CO_2	Reactivity of the mixture became higher than coal at 1200 °C or lower temperature, their reactivity became almost the same at a 1400 °C	[102]
Genesee coal, fluid coke, sawdust	Drop tube furnace *ID*: 0.06 m *H*: 1.4 m	Coal, coke: 53–75 Biomass: 250–300	*T*: 700–1400 °C	N_2	Increased reactivity at higher biomass blending ratio at low temperatures	[6,103]
50% low rank coal+50% petcoke, dealcoholozed grape ma	Entrained flow *ID*: 0.06 m *L*: 1.2 m Thickness: 0.07 m	–	Biomass (%wt): 0,10,30,50,80,100 *T*:750-1150 °C Fuel/air: 2.5–7.5	Air	Synergies observed at 750–850 °C and fuel /air: 2.5 For 80% biomass and 20% coal–coke for all temperatures, H_2 contents is maximum	[7]
High-ash coal, High-sulfur petroleum coke, wheat straw, barley straw, pine wood, olive tree, wine tree, cynara	Pressurized entrained flow		Biomass ratio: 10% *T*: 1700–1900 °CO_2 ratio:0.69–0.75 Nm^3/kg H_2O/fuel (kg/kg): 0.08–0.18	O_2 Steam	Gas composition (vol. %): H_2: 20–23; CO_2: 2–5; CO: 58–62 Cold gas efficiency (vol%): 75.5–77.5	[104]
Refuse derived fuel (RDF), lignite	British gas-lurgi moving bed		*T*: 700–2000 °C *P*: 27–30 bar Lignite: 3.36 ton/h RDF: 10.1 ton/h O_2: 0.2 m^3/m^3	Air–steam	Techno-economic, feed stock & production feasibility, environmentally and commercially process	[105]
Mulia coal, Japanese cedar	Downdraft fixed fed *ID*: 0.022 m, *H*: 0.7 m	500–1000	Biomass ratio: 0–1 *T*: 900 °C *P*: 101 kPa Air /fuel: 0–0.5 H_2O/fuel: 2,3	Air–steam	Conversion to gas (%): 59–98 Conversion to char (%): 36-1 Conversion to tar (%) : 7-1 Gas composition (vol. %): H_2: 47.9–37.5; CO_2: 26.1–33.7; CO: 22.1–23.9; CH_4: 2. 6-4.6; C_2H_6 & C_2H_4: 0.8–2.9 Cold gas efficiency (%): 65–85	[106] [107]
Bituminous coal (PT), olive stone (OS), chestnut tree residue (CH)	Fixed bed *ID*: 0.02 m *H*: 0.455 m	1000–2000	Biomass (%): 0–100 *P*:101 kPa FR: 150 cm^3/min	Steam O_2/N_2	Gas composition (vol.%): H_2: 9.4–22.1; CO_2: 16.3–19; CO: 6.2–14.1; CH_4: 1–1.3 Tar mass yield (%): 5–13	
Coal (PT), Pet coke(PC), almond shells (AS), olive stone (OS), eucalyptus(EB)	Pressurized tubular reactor *ID*: 0.013 m *H*: 0.305 m	75–150	Biomass (%): 0,5,10 *T*: 850–1000 °C *P*: 0.5–20 MPa FR:200 Ncm^3/min	Steam O_2/N_2	The addition up to 10%, led to increase in H2 and CO Gas yield (m^3/kg): 2.1–2.3 Cold gas efficiency (%): 69–77.7 Carbon conversion (%): 62.7–71 High heating value (kJ/Nm^3): 6223–6276	[5,33]
Bituminous shenmu coal, pine sawdust, rice straw	Fluidized bed *ID*: 0.12 m *H*: 1.578 m	Biomass: 420 Coal: 250–750	Biomass(wt%):0–33, *T*:921–1033 °C H_2O/carbon: 0.26–0.88 *ER*: 0.3–0.42 FR (coal) kg/h: 2–3, (pine): 0–1	Steam O_2/N_2	*T*=953 °C *ER*: 0.34 H_2O/carbon: 0.51 Gas composition (vol%): H_2: 20.71; CO_2: 19.43; CO: 29.13; CH_4: 2.54:SGY:1 Carbon conversion: 88.89% Gas efficiency: 60.92 %	[108]
Sub Bituminous A, Colombian coal, Rice husk, Sawdust, Coffee husk	Fluidized bed *ID*: 0.22 m *H*: 0.400 m	Coal: 1160 Rice husk: 1240 Sawdust: 1620 Coffee husk: 1630	Biomass (wt%): 6&15 *T*: 800–850 °C *P*: 101 kPa H_2O/fuel:0.1–0.8 kg/kg, Air/fuel: 2–3 kg/kg FR: 8 kg/h	Air–steam	Maximum gas composition (vol%): H_2: 15; CO_2: 10; CO: 11; Maximum LHV(MJ/m^3): 4.4 Maximum gas efficiency: 61%	[55]
Puertollano coal, bagasse, pine	Circular in cross-section fluidized bed *ID*:0.07 m *H*: 0.5 m	1250–2000 Silica sand: 350	Catalyst: Dolomite Biomass (%): 0–70 *T*.: 730–900 °C Steam: 4.9–7.8 g/m O_2/fuel: 0–0.6 g/g FR: 5.2–7.5 g/m	O_2 Steam	At *T*: 850–900 °C Maximum H_2: 45% Minimum gaseous hydrocarbons: 55% At O_2/fuel: 0.6 g/g Minimum gaseous hydrocarbons: 30% Maximum biomass content: 40%	[12]
Puertollano coal, Pine wood, Sawdust, Plastic waste: PP+EPRD+T20, PE-90563741	Bubbling fluidized bed *ID*: 0.092 m	Silica sand: −630+400, Dolomite: −800+400	Catalyst: Dolomite Coal: 60 wt%	Air	*T*: 850 °C ER: 0.36	[54]

Table 2 (*continued*)

Sample	Gasifier, specification	Particle size (μm)	Operating condition	Medium	Optimum obtained results	Ref.
	H: 1 m		Pine: 20 wt% Plastic: 20 wt% *T*: 740–880 °C FR: 1–4 kg/h P: 101 kPa FR:1.5–4 kg/h ER: 0.3–0.46		Gas composition (%) H_2: 7–15; CO_2: 14–23; CO: 10–20; CH_4: 2–10; C_2H_n:1–5 LHV (MJ/m^3): 4–8 Gas yield (m^3/kg): 1.5–5 Char yield (g/kg): 120–350 Tar content (g/m^3): less than 0.5	
Indonesian tinto coal, quercus acutissima sawdust	Dual circulating fluidized bed Combustor: *H*: 0.04 × 0.11 × 4.5 m Gasifier: *H*:0.04 × 0.285 × 2.13 m	Coal: 348 Biomass: 1438	Biomass: 0, 0.25, 0.5, 0.75, 1 *T*: 750–900 °C FR: 6.17–10.3 kg/h H_2O/fuel: 0.5–0.8 Fluidization gas velocity: 0.16–0.26 m/s	Air Steam	Biomass ratio: 0.5 *T*: 800 °C Gas product calorific value (MJ/m^3) With coal: 9.89–11.15 With biomass: 12.10–13.19 With coal/biomass: 13.77–14.39 Cold gas efficiency: 0.45	[11]
Daw Mill coal Silver birch wood	Pressurized fluidized bed *ID*: 34 mm *H*: 504 mm Thickness: 4 mm		Coal (%): 0–100 *T*: 850–1000 °C *P*: 0.1–2.5MPa	CO_2	Tar yield (%): 25–0 Total volatile yield (%): 95-45	[109]
Sabero coal, Black coal, Pine chips	Continuous fluidized bed *ID*: 0.043 m *H*: 0.2 m	750–1200	Blend (% wt/wt): 0/100–100/0 *T*: 840–910 °C *P*: 0.14 MPa *FR*: 0.86–1.24 kg/h Steam/air: 0.44–1.01 Fluidized gas velocity: 0.7–1.4 m/s	Air–steam	Pine chips/black coal: 25/75& pine chips/sabero coal: 40/60 Molar gas composition: H_2:13.05,11.58; CO_2:8.39,8.44; CO:16.81, 17.55;CH_4: 1.63, 1.88; C_nH_m: 0.31,0.37 LHV(MJ/m^3): 4.29,4.35 Gas yield(m^3/kg): 2.46, 1.78 Thermal efficiency (%): 61,54 Carbon conversion (%): 75.3,66.4	[68]
Coal, Pine, PE	Fluidized bed ID: 0.2 m *H*: 3.2 m	1250–2000	Pine: 20 wt% Coal: 40 wt% Plastic:20 wt% *T*: 750–900 ° *P*: 101 kPa O_2/fuel: 0.03–0.33 kg/kg O_2/steam:0.02–0.28 kg/kg FR: 3.3–3.5 kg/h Steam flow rate: 2–5 kg/h	Air Steam	*T*: 900 °C O_2/fuel: 0.33 kg/kg O_2/steam: 0.28 kg/kg H_2 concentration increased to70%; CH_4 concentration o- 30%. Hydrocarbon concentration decrease to 36%	[14]
Subbituminous: Montana Rosebud, Bituminous: Pittsburg #8, Furniture Sawdust: Niagra/Mohawk #1	Pressurized fluidized bed ID: 0.25 m *H*: 2.9 m	Coal: −1200–250 Biomass: −1200	Biomass (%wt.): 15,25,35 *T*: 900 °C *P*: 3030 kPa FR: 31.8–40.9 kg/h	Air	Biomass: 35 wt% Carbon conversion: 93%	[110]
Coal–coke (50%wt) Pinus pruning wastes, olive pruning wastes, grapevine pruning wastes, sawdust wastes, marc of grape	Circulating fluidized bed *ID*:0.075 m *H*: 1.2 m Width: 0.075 mm	< 800	Biomass (%): 0, 10, 30, 50, 70, 90 *T*: 750–1350 °C *FR*: 0.65–2.85 kg/h Biomass/air: 2–6	Air	Grapevine Pruning Wastes Biomass/air: 5.7 Gas composition (vol. %): H_2: 14; CO: 25; CH_4:5	[37]
Pine & PE	Circular fluidized bed *ID*: 0.07 m *H*: 0.5 m	1250–2000	Plastic (%): 10, 20, 40 *T*: 730–900 °C H_2O/waste: 0.4–0.9 FR: 5.7–12.5 g/min Flow rate of steam: 5.3 g/min	Steam	*T*: 885 °C Plastic (% w/w): 40 Gas composition (%v/v): H_2: 52; CO_2:7;CO: 30; CH_4: 7;C_nH_m: 1.7 HHV (kJ/Nl): 18.3 Gas yield (Nl/g): 1.96 Energy conversion(%): 98	[38]
Daw Mill coal, Straw, Miscanthus	Fluidized bed *ID*: 0.4 m		*P*: 1 MPa Fluidization velocity:0.8 m/s	Air Steam	Carbon conversion: above 80%	[111]

	H: 4 m					
Puertollano coal, Colombian coal, (RDF), Olive oil, bagasse, Pine, PE	Fluidized bed ID: 0.2 m *H*: 3.7 m	1250–2000	Catalyst: Dolomite, Ni-based Biomass (%): 0, 10, 20, 40, 100 *T*: 850 °C Steam flow rate: 5 kg/h FR: 6 kg/h ER: 0.2	Steam–Air	With dolomite: Tar reduction:80% NH_3 reduction: 30%, 50% H_2S reduction: 68%, 74% Overall treatment: NH_3 and H_2S reduction: higher than 97%	[112,113]
Birch, Daw Mill & Polish coal	Pressurized fluidized bed *ID*: 0.144 m *H*: 0. 6 m	Birch: 1000–3000 Daw mill coal: 1000–1350 Polish coal: 900–1350	Coal/wood: varied *T*: 700–900 °C *P*: 0.4 MPa	O_2	Brich wood/daw mill coal Gas yield (Ndm^3/kg): 683–1005 Char yield (wt%): 0–38.1 Tar yield (g/kg): 9.1–34.8 Brich wood/polish coal Gas yield (Ndm^3/kg): 335–850 Char yield (wt%): 0–8.9	[73]
Sub bituminous-Antiquia-Colombia coal, Pinus Patula& Cypress sawdust	Pressurized fluidized bed ID: 0.0 m *H*: 0.4 m	Wood: +100/200 Coal: +10/16	Coal (%v/v): 0, 5, 10, 20, 30 *T*: 850 °C	Steam	Gas composition (% v/v): H_2: 59; CO_2:20; CO: 6; CH_4: 5 HHV(MJ/Nm_3): 7.1–9.5	[114]
Puertollano coal, Edible oil waste	Bubbling fluidized bed *ID*: 0.0 8 m *H*: 1.5 m	1250–2000 Sand: 350	Waste (%): 0, 2.5, 5, 7.5, 10 *T*: 750–900 °C Steam flow rate: 5 g/min, Air flow rate: 1–11 g/min, *FR*: 6 g/min, O_2/fuel: 0.08–0.2 g/g	Air Steam	*T*: 850–900 °C Waste content: as low as 10% HHV (MJ/Nm^3): 20	[26]
Puertollano coal, Pine, Petcock, PE	Bubbling fluidized bed *ID*: 0.080 m *H*: 1.5 m	Coal, pine and pet coke: 1250–2000, *PE* ≤ 5000, Silica sand: 350	Biomass (%): 10, 20 Plastic (%): 10, 20 Catalysts: Calcined dolomite, Dolomite enriched with Nickel, Olivine, Nickel and magnesium oxides, Zinc oxide and cobalt and molybdenum oxides *T*: 850 °C Steam flow rate: 5 g/min *FR*: 6 g daf/min	O_2 Steam	A classification of catalyst activity: Dolomite > Ni–dolomite > plivine > Ni–Mg Dolomite led to highest H_2S reduction about 90%	[115]
Forest waste, waste slot machines, waste furniture, waste pallets, demolition wood residue, escatrón lignite	Fluidized bed *ID*: 0.043 m *H*: 1.025 m	750–1200	*T*: 840–950 °C Air/fuel (m^3/kg): 1.1–1.4 & 0.3–0.5 Steam/air (kg/m^3): 0.50–0.55	Air, Steam	Forest waste: Gas LHV (MJ/m^3): 5.4 Carbon conversion (%): 97 Gasification efficiency (%): 68 Tar contents (g/m^3) with secondary air: Forest waste: 3.7–0.72 Escatron lignite: 2.5–0.8	[95]

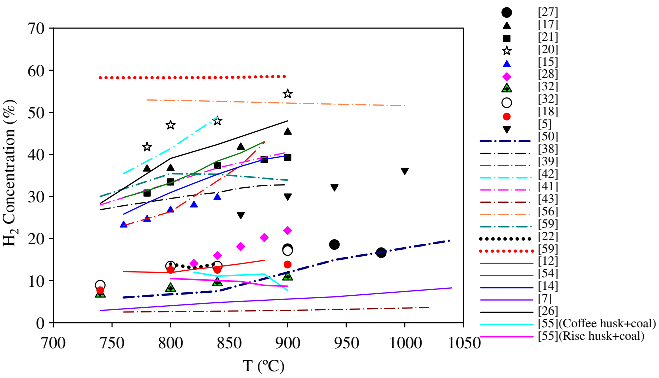


Fig. 1. Effect of temperature on H_2 production during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

gasification of holm-oak and eucalyptus are more than that from pine wastes gasification because the water gas shift reaction plays a main role during the gasification of holm-oak and eucalyptus. It is also explained that the presence of metal oxides in char tend to play the role of catalysts during the water gas shift reaction [39]. In catalytic biomass gasification (CBG) using different catalysts, such as sand, alumina, alumina with nickel, Rh/ CeO_2/SiO_2, steam reforming catalyst or dolomite lead to the production of higher amounts of hydrogen than non-catalytic routes due to high rate of water gas and cracking reactions[23,53]. Mahishi and Goswami [45] have presented a novel technique for increasing the H_2 production. They have gasified pine bark in the presence of calcium oxide and reported that the concentration of H_2 in the presence of sorbent (CaO) increased with the rise of temperature. Moreover, they have found that H_2 contents in gasification with sorbent are higher than that without sorbent [45].Temperature and residence time have a simultaneous effect on the BG and the results indicate that at a lower air pressure the residence time of air increases due to a lower air velocity, as a result of which the production of H_2 also increases at all temperatures [48].

Recently most researchers investigated COG of different kinds of coal and biomass samples and obtained the same trend for H_2 production at various temperatures like in the case of individual CG and BG processes [7,12,14,26,28,38,54]. However, the COG of coal with biomass having higher volatile matter and less humidity such as coffee husk or plastics like PET produced less contents of H_2 than CG alone [55]. It was also explained that high volatile matter contents improved the release of combustible gases, which required a lower process temperature and hence caused a reduction in H_2 concentration. Moreover, for the biomass having less content of volatile matter (rice husk) a higher temperature was required to obtain good products of combustion [12,28,55]. However, results showed that simultaneous increase in biomass content and temperature in COG led to higher contents of hydrogen [7]. On comparing COG having pine and PE with BG, more H_2 was produced than for pine gasification alone when the temperature increased due to further cracking of PE which required the supply of high thermal energy [38]. Types of fuel, such as coal (rank of coal) and biomass are very important factors for high yields of H_2. Generally, biomass having low contents of volatile matter and low ranked coal are more suitable for significant H_2 production because low ranked coals have higher reactivates than higher ranked ones [34]. Results of H_2 production during CG, BG and COG are shown in Fig. 1.

3.1.2. CO_2 concentration (%)

During CG using different coals (Brown, Fugu and Shenwha) at low temperature ranges high amounts of CO_2isproduced due to the oxidation and water gas shift reactions which are highly exothermic in nature. However, upon increasing the temperature the CO_2 level starts decreasing due to an increase in the rate of endothermic reactions such as Boudouard reaction which involves the consumption of CO_2 [15,27,28,30]. Moreover, in CCG, the production rate of CO_2 is smaller than in NCCG due to higher rate of endothermic reactions at higher temperatures [20,32] as shown in Fig. 2. At all temperatures during gasification of coals with higher carbon contents, more CO_2 is produced than from other ranks of coal because the production of main gases is dependent on the carbon contents of the fuels [96].

In BG, a similar trend as that of CG is observed for the production of CO_2 with the rise of bed temperature as shown in Fig. 2. This may be due to the increase in the rate of Boudouard reaction and the decrease of water gas shift reaction which causes a reduction in CO_2 content [23,37,40,42,44,50,52,56,57]. However, Pinto et al. [38] and Franco et al. [39] reported that CO_2 contents remained almost constant during the gasification of pine wastes because the water gas shift reaction was not important in theses pecies. They also claimed that use of eucalyptus and holm-oak biomasses for gasification purposes at a low temperature range of 730–830 °C caused an increase in the production of CO_2 due to the water gas shift reaction. However, at temperatures greater than 830 °C the contents of CO_2 start decreasing due to the Boudouard reaction [38,39,58]. Moreover, it is also observed that the contents of CO_2 during CBG are lesser in comparison to that of NCBG at all temperatures due to higher rates of endothermic reactions [23,43,59].

In case of COG, CO_2 production is more than that of CG because of higher oxygen contents in biomass than coal [14]. It is also reported that CO_2 production in COG with the rise in temperature is also reduced due to an increase in the consumption of CO_2 during dry reforming of CH_4/light hydrocarbons/tars as well as due to the influence of Boudouard reactions [12,14,26,28,38,54] (Fig. 2). Velez et al. [55] also observe the same phenomenon for a 6% CO_2 production during the COG of coffee husk with Colombian coal. They describe that CO_2 contents are higher at a comparatively low temperature range of 810 to 850 °C due to the influence of the main water gas shift reaction. However, at high temperature ranges the Boudouard reaction becomes more dominant and hence causes a reduction in the concentration of CO_2.

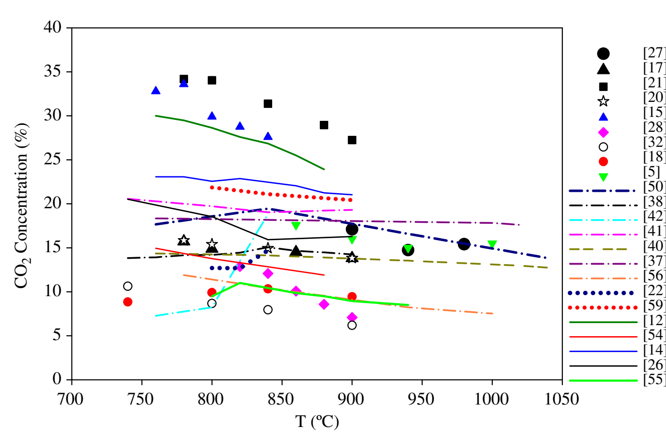


Fig. 2. Effect of temperature on CO_2 production during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

3.1.3. CO concentration (%)

With the rise of temperature, the CO production is also increased due to an increase in the rate of heterogeneous and endothermic reactions such as water gas and Boudouard reactions. In other words at higher temperatures carbon tends to react with steam (water gas reaction) and CO_2 (Boudouard reaction) to produce higher amounts of CO [17,27–29]. The results show that during the gasification of a bituminous coal with high volatility, CO increases from 5.8% at 850 °C to 17.4% at 1000 °C [5]. This increase is mainly observed in gasification of coals having higher contents of carbon. It is reported that during CG of PT coal, smaller amounts of CO is produced than from other coals (HV, DT and SA) due to a lower content of carbon in the former [33]. Simultaneous increase in both temperature and gas velocity in a fluidized bed system leads to higher contents of CO [18]. Moreover, in CCG higher amounts of CO are produced than NCCG because the rise in temperature not only increases the rate of water gas reaction but it also increases the activity of the catalyst [20,32].

In BG, similar results as that of CG are obtained for the CO production, i.e., the CO concentration increases with the rise in temperature due to an increase in the rate of both water gas and Boudouard reactions [23,37,40,44,48,50,52,56–60]. However, some other results show that the CO contents produced are initially low due to the water gas shift reaction and then increases due to the dominancy of the water gas, Boudouard and steam reforming reactions at high temperatures [25,41–43,45,47]. Franco et al. [39] describe that during BG using holm-oak and eucalyptus at a temperature range of 730 to 830 °C, lower CO is produced due to the water gas shift reaction. They also report that the presence of metal oxides in the char sample act as catalysts for the water gas shift reaction. It is also reported by Pinto et al. [38] that CO is mainly produced during oxidation reactions, which are exothermic in nature thereby lowering CO production with the rise of temperature [61]. CO contents in CBG are lower than that from NCBG because of a high rate of water gas shift reaction due to the presence of catalysts. However, CO concentration is slightly higher when $Rh/CeO_2/SiO_2$ are used as catalyst in comparison with others [23]. Hernandez et al. [48] conclude that at longer residence times in air for all temperatures studied, more CO is produced; however the effect of residence time on the production of CO is lower than that on H_2.

CO contents in COG are observed to be higher than that in CG due to the higher reactivity of biomass than that of coal as well as due to the presence of O_2 in biomass. In COG, the rise in bed temperature leads to an increase in the production of CO because of the dominancy of the Boudouard reaction over others [7,54,55]. It is also claimed that simultaneous increase in temperature and biomass contents can produce more CO [7]. Hernandez et al. [7] report that COG using 80% biomass and 20% coal can cause an increase of CO contents from 7.18 to 14% when temperature rises from 750 to 1050 °C. Pinto et al. [26] report the same and claim that at an elevated temperature of approximately 830 °C the CO production is slightly increased due to the consumption of CO_2 in dry reforming and Boudouard reactions [12]. Pohorely et al. [28] show that COG of brown coal with plastics (PET) give similar results as that of CG alone, i.e., with the rise in temperature, CO contents are also increased. The plots of the effect of temperature on the production of CO during CG, BG and COG of different kinds of coals, biomasses and plastics are shown in Fig. 3.

3.1.4. CH_4 and other hydrocarbons concentration (%)

Studies show that during CG, the concentration of CH_4 remains almost constant at low as well as at high temperatures. This is not because of the methanation reaction but it is mainly due to the pyrolysis process by which CH_4 is produced as this phenomenon has been claimed by numerous researchers [5,13,18,32]. However, a slight change in CH_4 production has been reported which is mainly due to the formation and consumption of CH_4 in exothermic reactions at low and high temperatures, respectively [28]. Kim et al. [15] have shown that with the rise of temperature, CH_4 starts decreasing from 16.7 to 8.9% at a temperature range of 750 to 850 °C. However, an opposite trend is observed for the rest of the hydrocarbons and their concentrations increase with the increase of temperature. This may be because of the use of low oxygen/coal ratio which causes reduction in reaction of volatiles hence the contents of hydrocarbons increase with the rise of temperature. Moreover, at all temperatures CH_4 decomposition takes place during CCG due to which the CH_4content is lesser than that from NCCG. It is also observed that during the bituminous CG, more heavy hydrocarbons are produced in comparison to lignite CG which usually produces high quantities of lighter hydrocarbons [34].

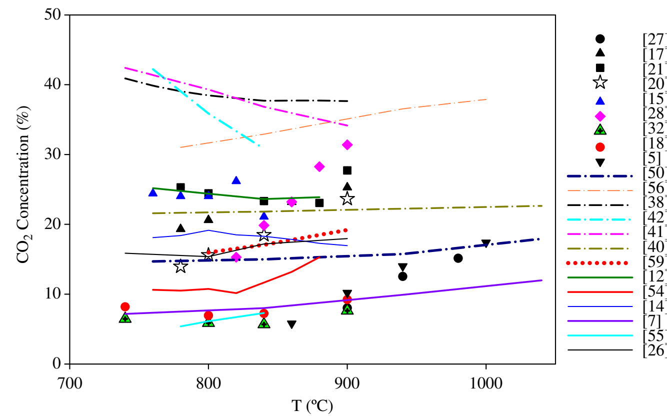


Fig. 3. Effect of temperature on CO production during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

It is reported that during BG, methane is produced by the heterogeneous and homogenous exothermic reactions (methanation and methane steam reforming).However, the combustion reaction starts consuming methane as a result of whichCH_4 concentration does not change significantly with the variation of temperature [37,50]. However, some researchers [22,38,39,57–59,61] have reported that contents of methane and other hydrocarbons slightly decrease with the rise in temperature due to further cracking and reforming reactions. It is also claimed that the effect of temperature on methane production is highly dependent on gasifying agents (air or steam) used. In air–steam BG, at elevated temperatures, more methane is produced while in air-BG the produced methane remains almost constant [62]. In CBG at higher temperatures less gaseous hydrocarbons are produced in comparison to that in NCBG due to the catalysis provided by the steam reforming and cracking reactions [59]. Moreover, it is also reported that in CBG over $Rh/CeO_2/SiO_2$ catalysts more methane is produced than from other catalysts or NCBG [23] indicating that methane production is also dependent upon the type of catalyst used.

In COG, with the rise of temperature, both methane and hydrocarbons decrease due to an increase in the reforming reactions [12,14,38,63]. It is also observed that the concentrations of hydrocarbons are higher in COG than in CG because of the biomass content in COG. The presence of this biomass lowers the temperature in COG than in CG, therefore the concentrations of hydrocarbons are comparatively higher than that from CG [55]. However, Pinto et al. [26] state that during COG of coal with edible oil waste, at temperatures higher than 850 °C, the concentration of C_nH_m decreases further due to the cracking and reforming reactions. During the gasification of pine wastes with plastics (PE), CH_4 and heavier hydrocarbons decrease more due to the reactions of PE molecules [38]. Aznar

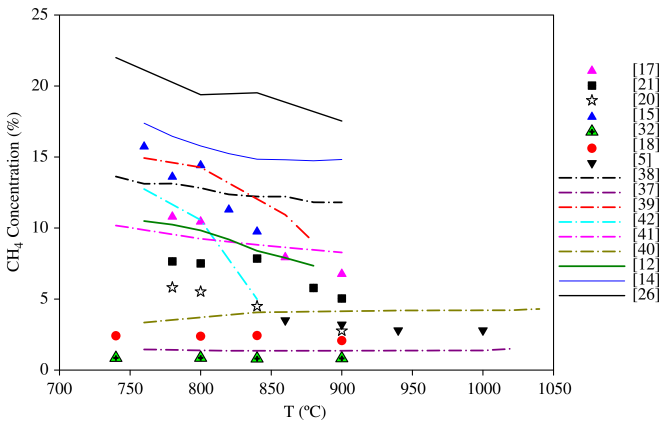


Fig. 4. Effect of temperature on CH_4 production during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

et al. [54] have also studied COG of coal, biomass and plastics and reported a slight increase in CH_4 contents at temperatures greater than 820 °C in the presence of dolomite due to an increase in the rate of the methanation reaction. However, they observe an opposite trend for the concentration of light hydrocarbons which decrease due to the cracking reactions. It is also claimed that at higher pressures more methane is produced with the rise of temperature because the formation of methane is strongly dependent on pressure [28,25]. The results of some studies are plotted in Fig. 4.

3.2. Carbon conversion

Carbon conversion is defined as the total carbon content of gas produced (CO, CO_2 and CH_4) during gasification to the total contents of the feedstock [5,17,18,32]. In CG using different coals (PT, Fugu, Australian and Shenwha), carbon conversion increases with the increase in temperature due to the oxidation and gasification reactions which cause high yields of gases from coal [5,15,17,27,29,64]. It is also reported that carbon conversion in CG not only depends on temperature but it is also a function of residence time or gas velocity at the same time. It is claimed that carbon conversion increases with the increase in residence time which causes a high rate of carbon reaction with steam and oxygen [18,65]. Moreover, low rank coals give high carbon conversion yields than semi-anthracite due to more reactivity, i.e., they react more easily and rapidly with the gasifying agents [33]. Similarly in CCG, with rise of temperature carbon conversion also increases but the yield is slightly more than that from NCCG. This increase may be attributed to the high rate of reaction in the presence of catalysts [32].

Trends in carbon conversion at different temperatures for BG are similar to that of CG. Researchers also came to the same conclusion that the increase in carbon conversion occurs with the rise of temperature, i.e., production of high yield of gas is achieved by oxidation and gasification reactions [11,39,41,44,50,51,61,66,67]. However, the carbon conversion is slightly higher than that from coal due to the presence of high volatile matter contents in biomass [11,67]. However, Lapuerta et al. [37] have reported that carbon conversion remains almost constant with the variation of temperature. They explain that with the rise of temperature volatile matter content increases but on the other hand residence time decreases. Asadullah et al. [66] have investigated the CBG using different catalysts and they stated that by increasing temperature over Rh/CeO_2/SiO_2 catalysts, carbon conversion seemed to be much higher than that in the presence of other catalysts or NCBG.

In COG, similar to that of CG and BG the carbon conversion also increases with the increase in temperature [67]. However, it is found to be less than that from BG but much higher than that from CG. High reactivity of biomass causes an increase in volatile matter, which subsequently gets converted to free radicals and therefore improves the decomposition, oxidation and gasification reactions. Due to both high reactivity and high contents of hydrogen and oxygen in biomass, carbon conversion during COG is greater than that in CG alone and this also tends to increase with increasing biomass contents in the fuel. Moreover, it is reported that because of higher carbon contents of low grade coals and production of more CO and CO_2 than high grade coals, carbon conversion increases in COG using low grade coals [68].

3.3. Gas yield

Gas yield is defined as the flow rate of total inert-free gas produced to mass flow rate of dry and ash free value of feedstock [5,12,17,38,39]. It has a very significant role because of its expression in terms of gas production with respect to the solid fuel [54]. The effect of temperature on gas yield during CG, BG and COG is shown in Fig. 5.

As carbon conversion increases with the rise in temperature hence gas yield also increases [5]. Seo et al. [11] and Kim et al. [15,17] have used different coals (Indonesian Tinto (Sub-bituminous), Australian coal and Shenwha) and found that gas yield increases with the increase in temperature due to pyrolysis, char gasification, steam reforming and cracking of hydrocarbons. In addition, in CCG gas yield is more than that from NCCG due to the increase in gaseous products. At atmospheric pressures, gas yield using semi-anthracite coal is higher than that from medium and high volatile bituminous coal because it has high carbon content [33]. However, at 15 times the value of atmospheric pressure, gas yield increases due to a dilution effect [33]. It is also reported that with the increase of both temperature and fluidizing gas velocity, the gas yield is also enhanced due to an increase in coal reactivity and gas production at particular conditions [18].

Numerous researchers have described the influence of temperature on gas yield in BG and they have found similar results as that of CG [11,16,22,39,40,42,43,50,61,69–72]. They claimed that with an increase in temperature, total gas yield also increased due to high releases of gaseous products from further pyrolysis, steam reforming, gasification and cracking reactions. Lahijani and Zainal [50] have reported that with the increase in temperature from 650 to 1050 °C, gas yield also increased from 1.36 to 2.10 Nm^3/kg for EFB and from 1.28 to 1.95 Nm^3/kg for sawdust, respectively. Seo et al. [11] have reported that due to the consumption of more biomass during its pyrolysis, total gas yield is more than that from

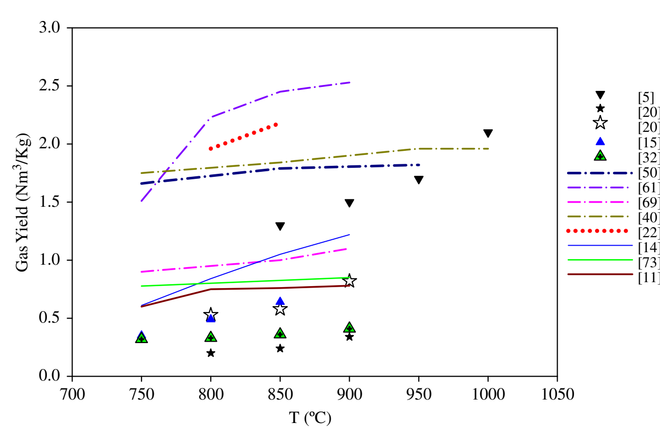


Fig. 5. Effect of temperature on gas yield during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

coal with the rise in temperature. In CBG, the gas yield increases more by changing the temperature due to an increase in the amounts of gaseous products [22,69].

In COG, gas yield also increases by increasing temperature due to the similar reasons as those of CG and BG [14,26,38,73]. In COG of coal with baggase, gas yield is higher than from CG due to greater hydrocarbon concentrations which result in the release of more gaseous products [12]. Seo et al. [11] have investigated the simultaneous effect of biomass and temperature on gas yield. They reported that from 750 to 900 °C, gas yield increased from 0.38 to 0.65 Nm^3/kg for COG using 75% coal and 25% biomass, 0.6 to 0.78 Nm^3/kg for COG using 50% coal and 50% biomass and 0.64 to 0.78 Nm^3/kg for COG using 25% coal and 75% biomass, respectively. This clearly indicates that at all temperature ranges from 750 to 900 °C, an increase in biomass ratio resulted in an increase in gas yield due to transfer of hydrogen radicals from biomass to coal that caused decomposition of coal [11]. Moreover, gas production in COG was higher than CG and lower than BG alone due to lower activity and the presence of less volatile matter in coal than in biomass [11].

3.4. Calorific value

Calorific value or heating value of a fuel is defined as the quantity of heat released by combusting a specific amount of fuel under normal conditions. It is expressed as high heating value (HHV) or gross calorific value, and low heating value (LHV) or net calorific value (NCV) [74]. It is reported that heating value depends on the contents of CO, H_2 and CH_4 [49,75]. Fig. 6 shows the results of some studies in CG, BG and COG.

Fermoso et al. [5] have investigated CG in a fixed bed reactor and described that with the increase in temperature the gas yield also increases which results in an increase in HHV. They explained that coals like DT and SA produce more H_2 than PT, due to more activity and high reactivity with steam. Thus these coals have higher HHV [33]. However, Seo et al. [11] somehow found opposite results using dual circulating fluidized bed reactors to that reported by Fermoso et al. [5]. They reported that the calorific value of gaseous products decreased due to the decline in hydrocarbon contents. It was also reported by Kim et al. [17] that in internally circulating fluidized beds (ICFBs), the increment of decomposition rate caused a decrease in calorific value, whereas in another set of experiments in a downer reactor [15], calorific value increased due to a rise in gaseous products. Calorific value in CCG is found to be lower than in NCCG due to the higher decomposition of hydrocarbons. However, at higher temperatures, it also increased due to the higher rate of water gas reaction than the decomposition reaction [20]. Lee et al. [18] concluded that with the increase in both temperature as well as fluidizing gas velocity, calorific value also increased. They stated that more H_2, CO and CH_4 were produced due to gasification and rapid pyrolysis reactions.

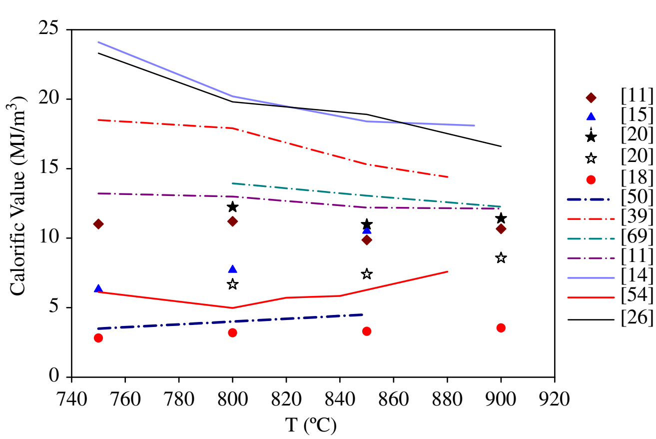


Fig. 6. Effect of temperature on calorific value during all gasification processes [CG: non-catalytic (bold symbol), catalytic (open symbol); BG: non-catalytic (dash dot line), catalytic (dot line); COG: non-catalytic (solid line)].

In BG, with the increase of temperature the calorific value reduces because of a decrease in the concentration of hydrocarbons [11]. However, the calorific value in biomass is more than that of coal at the same temperature because of high gas yields of CO and CH_4 [11]. Some other researchers have also observed the same phenomenon, i.e., with the increase in temperature, heating value decreases. They have explained that it is not only the decrease of hydrocarbon contents that involve a reduction in calorific value but the increase of hydrogen composition also has a significant contribution [39,76,77]. Pfeifer et al. [69] have claimed that both an increase in temperature and the use of catalyst cause a decrease in LHV because of the higher production and consumption of H_2 and CH_4, respectively. However, in BG of some specific biomasses such as coconut shells, palm kernel shells and rice hulls; instead of decreasing LHV and HHV increase due to an increase in gaseous products [40,50,72,78,79]. Encinar et al. [47] and Lv et al. [61] describe that HHV and LHV initially increase prior to a decrease because of the CO contents, which are more than H_2 at lower temperatures. However, at high temperatures they start decreasing due to thermal cracking and steam reforming. It is also reported that the gaseous heating value is more sensitive to the influence of temperature in the air–steam which acts as a gasifying agent. During BG, at higher temperatures, heating value is more in the air stream than in an air-BG due to higher contents of H_2 and CH_4 as a result of the presence of steam [62].

Andre et al. [12] state that in COG, HHV is found to be higher than CG because of higher amounts of gases having larger HHV and high biomass contents in COG. In COG studies, with the rise of temperature, LHV is increased because of an increase in H_2 production [7,54]. However, Andre et al. [12] and Pinto et al. [14,26] illustrate that HHV decrease due to a reduction in the contents of methane and hydrocarbons.

3.5. Cold gas efficiency

Cold gas efficiency can be calculated as the heating value of total gas production rate to the heating value of the feed rate [5,7,17,18,80]. In CG, it is found that due to the increase in gas yield and heating value of the produced gas at elevated temperatures, cold gas efficiency also increases [5,13,15,18,51,81,82]. It is also reported by Lee at al. [18] that the increase in both gas velocity and temperature cause an increase in cold gas efficiency. The results show that in CCG, cold gas efficiency is higher than NCCG due to the higher gas yield at the same temperature [20]. However, Minchener et al. [83] have found the opposite phenomenon and state that in a single stage fluidized bed reactor at low temperatures the carbon conversion is not complete due to which the cold gas efficiency is lower than that in other gasifiers. Cold gas efficiency of different ranks of coal has a similar trend as that of HHV. The semi-anthracite (HV) has the lowest HHV among different coals because of the lower HHV of the produced gas and also the high HHV of the semi-anthracite, while DT and SA coals have the highest HHV because they react easily in the presence of oxygen and steam [33].

In BG, numerous researchers have obtained similar effects on cold gas efficiency with the variation of temperatures as that for CG [11,23,40,48,50]. However, the value of cold gas efficiency in BG is more than that of CG because of a higher yield in the gaseous product during BG as observed by Seo et al. [11]. It is also

reported that by a simultaneous increase of space time and temperature, cold gas efficiency increases more because of a large increase in H_2 and CO contents as well as LHV gaseous products [48]. In CBG, cold gas efficiency also increases because of an increase in CO and H_2 concentrations at higher temperatures. The results show that at the same temperature, $Rh/CeO_2/SiO_2$ catalysts produce higher contents of H_2 and CO which results in greater cold gas efficiency in comparison to the effect of other catalysts or NCBG.

Hernandez et al. [7] have investigated the cold gas efficiency during COG for a simultaneous variation in temperature and biomass content. They report that during COG of 50% biomass and 50% coal and COG of 80% biomass with 20% coal, cold gas efficiency increases from 8 to 20% and 15 to 28%, respectively, with the increase of temperature from 750 to 1050 °C. These results show that cold gas efficiency increases by increasing both temperature and biomass contents due to an increase in H_2 and CO contents as well as the gas heating value [7].

3.6. Tar contents and char yield

Tar consists of condensable hydrocarbons such as single ring to 5-ring aromatic compounds, oxygen-containing hydrocarbons and mostly polycyclic aromatic hydrocarbons (PAH) [75,84,85,86,87]. According to the EU/IEA/US-DOE in Brussels (1998), tar is defined as all organic components with a molecular weight and boiling point higher than benzene [60,88,89]. It is mostly produced in the pyrolysis zone and its physical properties are affected by temperature and heating rate [90].Tar is one of the most unpleasant by product during gasification. It causes environmental and operational problems such as condensation, tar aerosol formation and polymerization that clog the pipelines and block process operations [55,84,85,88,90–94].

The results from Pan et al. [95] show that tar contents are higher in BG than in CG at the same temperature, and this is one of the major disadvantages of BG (i.e., formation of tar).It restricts the quick and wide spread use of H_2 [35].It can be reduced by using thermal cracking or catalysts. It is reported that by increasing temperature, tar is converted to H_2, CO and lighter hydrocarbons. This increase in temperature causes an increase in endothermic reactions such as tar cracking and steam reforming [42,49,63,71,88,96–100]. Cao et al. [85] studied the temperature of the reactor (both top and bottom) and reported that an increase in temperature at the top of the reactor causes less production of tar contents than at the bottom of the reactor. It is reported that the temperature has a significant influence on both the production and properties of tar and this influence is mainly by the chemical reactions in gasification [51]. Tar compositions changed from alkyl-substituted poly-aromatic hydrocarbons (PAH) to non-substituted PAHs by increasing temperature [51]. However, it is claimed that tar in BG is quite hard to crack by thermal treatment alone and hence three different methods are suggested: (1) increasing residence time, (2) direct contact with heated surface or (3) partial oxidation. However, these methods are partly effective and raise the cost of the process [87]. It is also explained in the literature that a simultaneous increase in temperature and residence time can improve tar cracking, gas production and char quality [87]. In CBG, results show that tar decreases more by further cracking and reforming reactions. It is also reported that the activity of catalysts can be increased with the rise of temperature [22,23,43,66,69,78,92,101].

In COG, tar concentration decreases with the increase of temperature due to cracking and reforming of tars [6,7,26,28,54]. On the other hand, upon increasing biomass in COG, tar contents are increased because biomass plays a key role in producing tar [54].

Char consists of un-reacted carbon which is produced more in CG because of lower reactivity of coal than that of biomass [54]. However, char yield decreases with the increase of temperature due to cracking and char reactions [22,39,42,71,73,97,101]. The results from Sjostrom et al. [73] show that during COG, char yield decreases by reducing the amounts of coal and increasing temperature. Moreover, it can be seen that char yield in COG is found to be higher than that in BG and lesser than that in CG [73].

4. Conclusions and recommendations

This review widely reports the effect of temperature on gasification products under catalytic and non-catalytic conditions for CG, BG and COG processes as it plays a very significant role in all gasification processes. It is observed that H_2, CO, carbon conversion and cold gas efficiency are increased while on the other hand CO_2, CH_4, hydrocarbons and tar contents are decreased with the rise of temperature. This is mainly due to the involved endothermic reactions in the gasification process which become more dominant at higher temperatures. Similar behaviour is also found during catalytic gasification. Moreover, it is also observed thatthe high reactivity of biomass contents also reflects on the temperature as well as gasification products. In practice, gasification is dependent on various parameters such as temperature, pressure, types of fuel used (coal and biomass or their blends) and the fuel/gasifying agent ratio. In addition, these parameters are equally important and correlated with each other during gasification but temperature is the most significant one amongst them. COG can be improved by finding optimum values of these aforementioned parameters. It can be concluded that COG seems to be a promising technology, which can reduce the consumption of fossil fuels and increase the use of renewable resources, such as biomass and wastes. Also it produces less unpleasant products like tar and has higher carbon conversion and gas yield than CG and BG. For future prospects, more technologies need to be developed, such as coal and biomass co-firing and beneficiation, which can maximize the yield of hydrogen production and mitigate CO_2, N_2 and sulfur emissions as these are some of the main challenges, i.e., to enhance the H_2 concentration either by using the water gas shift reaction or by any other means and simultaneously or subsequently capture and sequester the CO_2. It is not of much consequence whether the concentration of the produced CO_2 is high or low as numerous technologies have already been developed such as oxy-fuel combustion, pre-combustion and post-combustion techniques for capturing and sequestering high and low concentrations of CO_2, respectively.

Acknowledgments

The author would like to acknowledge the financial support from UMRG (University of Malaya Research) Grant RG 095/10AET.

References

[1] International Energy Outlook. 2011, 〈http://www.eia.gov/forecasts/ioe/index.cfm〉 [accessed on 30.05.2012].
[2] IEA, Key world energy statistics. 2011, 〈www.iea.org/textbase/nppdf/free/2011/key_world_energy_stats.pdf〉 [accessed on 30.05.2012].
[3] BP. Statistical review of world energy. 2011, 〈http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/statistical_review_of_world_energy_full_report_2011.pdf〉 [accessed on 30.05.2012].
[4] Saxena RC, Adhikari DK, Goyal HB. Biomass-based energy fuel through biochemical routes: a review. Renewable and Sustainable Energy Reviews 2009;13:167–78.

[5] Fermoso J, Arias B, Plaza MG, Pevida C, Rubiera F, Pis JJ, et al. High-pressure CO-gasification of coal with biomass and petroleum coke. Fuel Processing Technology 2009;90:926–32.
[6] Gao C. CO-gasification of biomass with coal and oil sand coke in a drop tube furnace. MSc thesis,University of Alberta, Canada; 2010.
[7] Hernandez JJ, Aranda-Almansa G, Serrano C. CO-gasification of biomass wastes and coal–coke blends in an entrained flow gasifier: an experimental study. Energy Fuel 2010;24:2479–88.
[8] Zhu W, Song W, Lin W. Catalytic gasification of char from CO-pyrolysis of coal and biomass. Fuel Processing Technology 2008;89:890–6.
[9] Brown RC, Liu Q, Norton G. Catalytic effects observed during the CO-gasification of coal and switchgrass. Biomass Bioenergy 2000;18: 499–506.
[10] Bi J CO-gasification of biomass and coal in a fluidized bed. In: 2nd biomass-Asia workshop; 2005.
[11] Seo MW, Goo JH, Kim SD, Lee SH, Choi YC. Gasification characteristics of coal/biomass blend in a dual circulating fluidized bed reactor. Energy Fuel 2010;24:3108–18.
[12] André RN, Pinto F, Franco C, Dias M, Gulyurtlu I, Matos MAA, et al. Fluidised bed CO-gasification of coal and olive oil industry wastes. Fuel 2005;84: 1635–44.
[13] Fermoso J. Pressure CO-gasification of coal and biomass for the production of hydrogen. PhD, University of Oviedo,Spain; 2009.
[14] Pinto F, Franco C, André RN, Tavares C, Dias M, Gulyurtlu I, et al. Effect of experimental conditions on CO-gasification of coal, biomass and plastics wastes with air/steam mixtures in a fluidized bed system. Fuel 2003;82:1967–76.
[15] Kim YJ, Lee SH, Kim SD. Coal gasification characteristics in a downer reactor. Fuel 2001;80:1915–22.
[16] Xiao X, Meng X, Le DD, Takarada T. Two-stage steam gasification of waste biomass in fluidized bed at low temperature: Parametric investigations and performance optimization. Bioresource Technology 2011;102:1975–81.
[17] Kim YJ, Lee JM, Kim SD. Coal gasification characteristics in an internally circulating fluidized bed with draught tube. Fuel 1997;76:1067–73.
[18] Lee WJ, Kim SD, Song B-H. Steam gasification of an Australian bituminous coal in a fluidized bed. Korean Journal of Chemical Engineering 2002;19:1091–6.
[19] Mondal P, Dang GS, Garg MO. Syngas production through gasification and cleanup for downstream applications—recent developments. Fuel Processing Technology 2011;92:1395–410.
[20] Lee JM, Kim YJ, Kim SD. Catalytic coal gasification in an internally circulating fluidized bed reactor with draft tube. Applied Thermal Engineering 1998;18:1013–24.
[21] Lee JM, Kim YJ, Lee WJ, Kim SD. Coal-gasification kinetics derived from pyrolysis in a fluidized-bed reactor. Energy 1998;23:475–88.
[22] Gil J, Caballero MA, Martin JA, Aznar MP, Caballero J. Biomass gasification with air in a fluidized bed: effect of the in-bed use of dolomite under different operation conditions. Industrial & Engineering Chemistry Research 1999;38:4226–35.
[23] Asadullah M, Miyazawa T, Ito S-i, Kunimori K, Koyama S, Tomishige K. A comparison of $Rh/CeO_2/SiO_2$ catalysts with steam reforming catalysts, dolomite and inert materials as bed materials in low throughput fluidized bed gasification systems. Biomass Bioenergy 2004;26:269–79.
[24] García-Ibañez P, Cabanillas A, Sánchez JM. Gasification of leached orujillo (olive oil waste) in a pilot plant circulating fluidised bed reactor. Preliminary results. Biomass Bioenergy 2004;27:183–94.
[25] Gil J, Corella J, Aznar MP, Caballero MA. Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of gasifying agent on the product distribution. Biomass Bioenergy 1999;17:389–403.
[26] Pinto F, Franco C, Lopes H, André R, Gulyurtlu I, Cabrita I. Effect of used edible oils in coal fluidised bed gasification. Fuel 2005;84:2236–47.
[27] Huang J, Yitian F, Chen H, Wang Y. Coal gasification characteristic in a pressurized fluidized bed. Energy Fuel 2003;17:1474–9.
[28] Pohorelý M, Vosecký M, Hejdová P, Puncochár M, Skoblja S, Staf M, et al. Gasification of coal and PET in fluidized bed reactor. Fuel 2006;85:2458–68.
[29] Fermoso J, Gil MV, Arias B, Plaza MG, Pevida C, Pis JJ, et al. Application of response surface methodology to assess the combined effect of operating variables on high-pressure coal gasification for H_2-rich gas production. International Journal of Hydrogen Energy 2010;35:1191–204.
[30] Harris DJ, Roberts DG, Henderson DG. Gasification behaviour of Australian coals at high temperature and pressure. Fuel 2006;85:134–42.
[31] Fermoso J. CO-gasification of coal and biomass for hydrogen production. MSc,University of Oviedo.,2007.
[32] Lee WJ, Kim SD, Song B-H. Steam gasification of coal with salt mixture of potassium and nickel in a fluidized bed reactor. Korean Journal of Chemical Engineering 2001;18:640–5.
[33] Fermoso J, Arias B, Gil MV, Plaza MG, Pevida C, Pis JJ, et al. CO-gasification of different rank coals with biomass and petroleum coke in a high-pressure reactor for H_2-rich gas production. Bioresource Technology 2010;101: 3230–5.
[34] Irfan MF, Usman MR, Kusakabe K. Coal gasification in CO_2 atmosphere and its kinetics since 1948: a brief review. Energy 2011;36:12–40.
[35] Ahmed TY, Ahmad MM, Yusup S, Inayat A, Khan Z. Mathematical and computational approaches for design of biomass gasification for hydrogen production: A review. Renewable & Sustainable Energy Reviews 2012;16:2304–15.
[36] Mohammed MAA, Salmiaton A, Wan Azlina WAKG, Mohammad Amran MS, Fakhru'l-Razi A. Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. Energy Conversion and Management 2011;52:1555–61.
[37] Lapuerta M, Hernández JJ, Pazo A, López J. Gasification and CO-gasification of biomass wastes: effect of the biomass origin and the gasifier operating conditions. Fuel Processing Technology 2008;89:828–37.
[38] Pinto F, Franco C, André RN, Miranda M, Gulyurtlu I, Cabrita I. CO-gasification study of biomass mixed with plastic wastes. Fuel 2002;81: 291–7.
[39] Franco C, Pinto F, Gulyurtlu I, Cabrita I. The study of reactions influencing the biomass steam gasification process. Fuel 2003;82:835–42.
[40] Hernandez JJ, Aranda G, San Miguel G, Bula A. Gasification of grapevine pruning waste in an entrained-flow reactor: gas products, energy efficiency and gas conditioning alternatives. Global NEST Journal 2010;12:215–27.
[41] Nikoo MB, Mahinpey N. Simulation of biomass gasification in fluidized bed reactor using ASPEN PLUS. Biomass Bioenergy 2008;32:1245–54.
[42] Wei L, Xu S, Zhang L, Liu C, Zhu H, Liu S. Steam gasification of biomass for hydrogen-rich gas in a free-fall reactor. International Journal of Hydrogen Energy 2007;32:24–31.
[43] Lv P, Yuan Z, Wu C, Ma L, Chen Y, Tsubaki N. Bio-syngas production from biomass catalytic gasification. Energy Conversion and Management 2007;48:1132–9.
[44] MA MS, NH HMY, Wan Ab, Karim Ghani WA. Gasification of biochar from empty fruit bunch in a fluidized bed reactor. Energies 2010;3:1344–52.
[45] Mahishi MR, Goswami DY. An experimental study of hydrogen production by gasification of biomass in the presence of a CO_2 sorbent. International Journal of Hydrogen Energy 2007;32:2803–8.
[46] Corella J, Toledo JM, Molina G. Biomass gasification with pure steam in fluidised bed: 12 variables that affect the effectiveness of the biomass gasifier. International Journal of Oil, Gas and Coal Technology 2008;1: 194–207.
[47] Encinar JM, Beltrán FJ, Ramiro A, González JF. Pyrolysis/gasification of agricultural residues by carbon dioxide in the presence of different additives: influence of variables. Fuel Processing Technology 1998;55: 219–33.
[48] Hernández JJ, Aranda-Almansa G, Bula A. Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time. Fuel Processing Technology 2010;91:681–92.
[49] Gil J, Aznar MP, Caballero MA, Francés E, Corella J. Biomass gasification in fluidized bed at pilot scale with steam–oxygen mixtures. Product distribution for very different operating conditions. Energy Fuel 1997;11:1109–18.
[50] Lahijani P, Zainal ZA. Gasification of palm empty fruit bunch in a bubbling fluidized bed: performance and agglomeration study. Bioresource Technoloy 2011;102:2068–76.
[51] Meng X, de Jong W, Fu N, Verkooijen AHM. Biomass gasification in a 100 kW h steam–oxygen blown circulating fluidized bed gasifier: effects of operational conditions on product gas distribution and tar formation. Biomass Bioenergy 2011;35:2910–24.
[52] Qin K, Lin W, Jensen PA, Jensen AD. High-temperature entrained flow gasification of biomass. Fuel 2012;93:589–600.
[53] Bulushev DA, Ross JRH. Catalysis for conversion of biomass to fuels via pyrolysis and gasification: a review. Catalysis Today 2011;171:1–13.
[54] Aznar MP, Caballero MA, Sancho JA, Francés E. Plastic waste elimination by CO-gasification with coal and biomass in fluidized bed with air in pilot plant. Fuel Processing Technology 2006;87:409–20.
[55] Vélez JF, Chejne F, Valdés CF, Emery EJ, Londoño CA. CO-gasification of Colombian coal and biomass in fluidized bed: an experimental study. Fuel 2009;88:424–30.
[56] Abuadala A, Dincer I, Naterer GF. Exergy analysis of hydrogen production from biomass gasification. International Journal of Hydrogen Energy 2010;35:4981–90.
[57] Haryanto A, Fernando SD, Pordesimo LO, Adhikari S. Upgrading of syngas derived from biomass gasification: a thermodynamic analysis. Biomass Bioenergy 2009;33:882–9.
[58] Song T, Wu J, Shen L, Xiao J. Experimental investigation on hydrogen production from biomass gasification in interconnected fluidized beds. Biomass Bioenergy 2012;36:258–67.
[59] Detournay M, Hemati M, Andreux R. Biomass steam gasification in fluidized bed of inert or catalytic particles: comparison between experimental results and thermodynamic equilibrium predictions. Powder Technology 2011;208: 558–67.
[60] Göransson K, Söderlind U, He J, Zhang W. Review of syngas production via biomass DFBGs. Renewable and Sustainable Energy Reviews 2011;15: 482–92.
[61] Lv PM, Xiong ZH, Chang J, Wu CZ, Chen Y, Zhu JX. An experimental study on biomass air–steam gasification in a fluidized bed. Bioresource Technology 2004;95:95–101.
[62] Hernández JJ, Aranda G, Barba J, Mendoza JM. Effect of steam content in the air–steam flow on biomass entrained flow gasification. Fuel Processing Technology 2012;99:43–55.
[63] Moghtaderi B. Effects of controlling parameters on production of hydrogen by catalytic steam gasification of biomass at low temperatures. Fuel 2007;86:2422–30.

[64] Ocampo A, Arenas E, Chejne F, Espinel J, Londoño C, Aguirre J, et al. An experimental study on gasification of Colombian coal in fluidised bed. Fuel 2003;82:161–4.
[65] Tremel A, Haselsteiner T, Kunze C, Spliethoff H. Experimental investigation of high temperature and high pressure coal gasification. Applied Energy 2012;92:279–85.
[66] Asadullah M, Ito S-i, Kunimori K, Tomishige K. Role of catalyst and its fluidization in the catalytic gasification of biomass to syngas at low temperature. Industrial & Engineering Chemistry Research 2002;41: 4567–75.
[67] Song X-c, Li K-Z, Wang J-f, Dong Z-b, Bi J-c. Experimental study on CO-gasification of biomass and coal. Journal of Fuel Chemistry and Technology 2006;34:303–8.
[68] Pan YG, Velo E, Roca X, Manyà JJ, Puigjaner L. Fluidized-bed CO-gasification of residual biomass/poor coal blends for fuel gas production. Fuel 2000;79:1317–26.
[69] Pfeifer C, Rauch R, Hofbauer H. In-bed catalytic tar reduction in a dual fluidized bed biomass steam gasifier. Industrial & Engineering Chemistry Research 2004;43:1634–40.
[70] Herguido J, Corella J, Gonzllez-Saiz J. Steam gasification of lignocellulosic residues in a fluidized bed at a small pilot scale. Effect of the type of feedstock. Industrial & Engineering Chemistry Research 1992;31:1274–82.
[71] Rapagnà S, Jand N, Kiennemann A, Foscolo PU. Steam-gasification of biomass in a fluidised-bed of olivine particles. Biomass Bioenergy 2000;19:187–97.
[72] Karim Ghani WAWA, Alipour Moghadam R, Mohd Salleh MA, Alias AB. Air gasification of agricultural waste in a fluidized bed gasifier: hydrogen production performance. Energies 2009;2:258–68.
[73] Sjöström K, Chen G, Yu Q, Brage C, Rosén C. Promoted reactivity of char in CO-gasification of biomass and coal: synergies in the thermochemical process. Fuel 1999;78:1189–94.
[74] McKendry P. Energy production from biomass (Part 1): overview of biomass. Bioresource Technology 2002;83:37–46.
[75] Natarajan E, Nordin A, Rao AN. Overview of combustion and gasification of rice husk in fluidized bed reactors. Biomass Bioenergy 1997;14:533–46.
[76] Van den Aarsen FG, Beenackers AACM, Vav Swaij WPM Performance of rice husk fluidized bed pilot plant gasifier. In: First intproducer gas conference; 1982.
[77] Panaka P Operating experience with biomass gasification in Indonesia. In:Advanced thermochememical biomass conversion; 1994, pp. 392–402.
[78] Li XT, Grace JR, Lim CJ, Watkinson AP, Chen HP, Kim JR. Biomass gasification in a circulating fluidized bed. Biomass Bioenergy 2004;26:171–93.
[79] Bingyan X, Zongnan L A study of fluidized bed gasification rice hulls. In: Advanced in solar energy technology, Biennial congress; 1987.
[80] Sugiyama S, Suzuki N, Kato Y, Yoshikawa K, Omino A, Ishii T, et al. Gasification performance of coals using high temperature air. Energy 2005;30:399–413.
[81] Xiao R, Zhang M, Jin B, Huang Y. High-temperature air/steam-blown gasification of coal in a pressurized spout-fluid bed. Energy & Fuels 2006;20:715–20.
[82] Xiao R, Zhang M, Jin B, Xiaong Y, Zhou H, Duan Y, et al. Air blown partial gasification of coal in a pilot plant pressurized spout-fluid bed reactor. Fuel 2007;86:1631–40.
[83] Minchener AJ. Coal gasification for advanced power generation. Fuel 2005;84:2222–35.
[84] Devi L, Ptasinski KJ, Janssen FJJG. A review of the primary measures for tar elimination in biomass gasification processes. Biomass Bioenergy 2003;24:125–40.
[85] Cao Y, Wang Y, Riley JT, Pan W-P. A novel biomass air gasification process for producing tar-free higher heating value fuel gas. Fuel Processing Technology 2006;87:343–53.
[86] Tzeng LM Characterization of bubbling fluidized bed biomass gasifier. MSc.,University of Sains Malaysia,2007.
[87] Anis S, Zainal ZA. Tar reduction in biomass producer gas via mechanical, catalytic and thermal methods: a review. Renewable and Sustainable Energy Reviews 2011;15:2355–77.
[88] Qin Y, Huang H, Wu Z, Feng J, Li W, Xie K. Characterization of tar from sawdust gasified in the pressurized fluidized bed. Biomass Bioenergy 2007;31:243–9.
[89] Neeft J, Knoef H, Onaji P Behaviour of tar in biomass gasification systems. Tar related problems and their solutions. Energy from waste and biomass (EWAB), Report no. 9919; 1999.
[90] Rajvanshi AK. In: Goswami DY, editor. Biomass gasification. India: Alternative Energy in Agriculture CRC Press; 1986. p. 83–102.
[91] Han J, Kim H. The reduction and control technology of tar during biomass gasification/pyrolysis: an overview. Renewable and Sustainable Energy Reviews 2008;12:397–416.
[92] Yu QZ, Brage C, Nordgreen T, Sjöström K. Effects of Chinese dolomites on tar cracking in gasification of birch. Fuel 2009;88:1922–6.
[93] Arena U, Zaccariello L, Mastellone ML. Tar removal during the fluidized bed gasification of plastic waste. Waste Management 2009;29:783–91.
[94] Arena U, Zaccariello L, Mastellone ML. Fluidized bed gasification of waste-derived fuels. Waste Management 2010;30:1212–9.
[95] Pan YG, Roca X, Velo E, Puigjaner L. Removal of tar by secondary air in fluidised bed gasification of residual biomass and coal. Fuel 1999;78: 1703–9.
[96] Ponzio A, Kalisz S, Blasiak W. Effect of operating conditions on tar and gas composition in high temperature air/steam gasification (HTAG) of plastic containing waste. Fuel Processing Technology 2006;87:223–33.
[97] Alauddin ZABZ, Lahijani P, Mohammadi M, Mohamed AR. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: a review. Renewable and Sustainable Energy Reviews 2010;14: 2852–62.
[98] Narvaez I, Orío A, Aznar MP, Corella J. Biomass gasification with air in an atmospheric bubbling fluidized bed. effect of six operational variables on the quality of the produced raw gas. Industrial & Engineering Chemistry Research 1996;35:2110–20.
[99] Chaiprasert P, Vitidsant T. Promotion of coconut shell gasification by steam reforming on nickel–dolomite. American Journal of Applied Sciences 2009;6:332–6.
[100] Corella J, Toledo JM, Molina G. Steam gasification of coal at low–medium (600–800 °C) temperature with simultaneous CO_2 capture in fluidized bed at atmospheric pressure: the effect of inorganic species. 1. Literature review and comments. Industrial & Engineering Chemistry Research 2006;45: 6137–46.
[101] Tomishige K, Asadullah M, Kunimori K. Syngas production by biomass gasification using $Rh/CeO_2/SiO_2$ catalysts and fluidized bed reactor. Catalysis Today 2004;89:389–403.
[102] Kajitani S, Zhang Y, Umemoto S, Ashizawa M, Hara S. CO-gasification reactivity of coal and woody biomass in high-temperature gasification. Energy Fuel 2010;24:145–51.
[103] Gao C, Vejahati F, Katalambula H, Gupta R. CO-gasification of biomass with coal and oil sand coke in a drop tube furnace. Energy Fuel 2010;24: 232–40.
[104] Valero A, Usón S. Oxy-CO-gasification of coal and biomass in an integrated gasification combined cycle (IGCC) power plant. Energy 2006;31:1643–55.
[105] Koukouzas N, Katsiadakis A, Karlopoulos E, Kakaras E. CO-gasification of solid waste and lignite—a case study for Western Macedonia. Waste Management 2008;28:1263–75.
[106] Kumabe K, Hanaoka T, Fujimoto S, Minowa T, Sakanishi K. CO-gasification of woody biomass and coal with air and steam. Fuel 2007;86:684–9.
[107] Fermoso J, Arias B, Pevida C, Plaza MG, Rubiera F, Pis JJ Hydrogen production from the CO-utilisation of coal and biomass. In: International conference on coal science and technology; 2007.
[108] Li K, Zhang R, Bi J. Experimental study on syngas production by CO-gasification of coal and biomass in a fluidized bed. International Journal of Hydrogen Energy 2010;35:2722–6.
[109] Collot AG, Zhuo Y, Dugwell DR, Kandiyoti R. CO-pyrolysis and CO-gasification of coal and biomass in bench-scale fixed-bed and fluidised bed reactors. Fuel 1999;78:667–79.
[110] McLendon TR, Lui AP, Pineault RL, Beer SK, Richardson SW. High-pressure CO-gasification of coal and biomass in a fluidized bed. Biomass Bioenergy 2004;26:377–88.
[111] de Jong W, Andries J, Hein KRG. Coal/biomass CO-gasification in a pressurised fluidised bed reactor. Renewable Energy 1999;16:1110–3.
[112] Pinto F, André RN, Franco C, Lopes H, Carolino C, Costa R, et al. CO-gasification of coal and wastes in a pilot-scale installation. 2: effect of catalysts in syngas treatment to achieve sulphur and nitrogen compounds abatement. Fuel 2010;89:3340–51.
[113] Pinto F, André RN, Franco C, Lopes H, Gulyurtlu I, Cabrita I. CO-gasification of coal and wastes in a pilot-scale installation 1: effect of catalysts in syngas treatment to achieve tar abatement. Fuel 2009;88:2392–402.
[114] Alzate CA, Chejne F, Valdés CF, Berrio A, Cruz JDL, Londoño CA. CO-gasification of pelletized wood residues. Fuel 2009;88:437–45.
[115] Pinto F, Lopes H, André RN, Gulyurtlu I, Cabrita I. Effect of catalysts in the quality of syngas and by-products obtained by CO-gasification of coal and wastes. 2: heavy metals, sulphur and halogen compounds abatement. Fuel 2008;87:1050–62.